Applied Nanotechnology for Human Space Exploration

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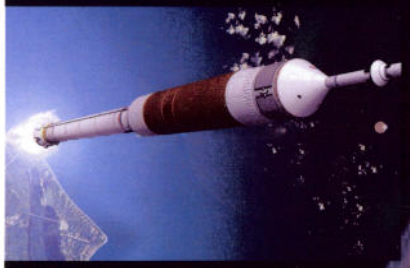
NASA's Strategic Vision



Deep Space Exploration

Mars Manned

Mars Robotic

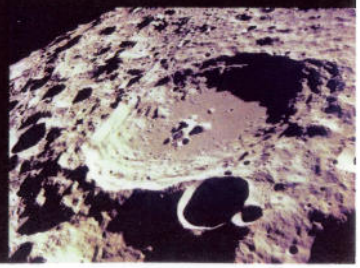
Crew Exploration Vehicle

Lunar Manned

Lunar Robotic

ISS Complete

2005 2010 2015 2020 2035

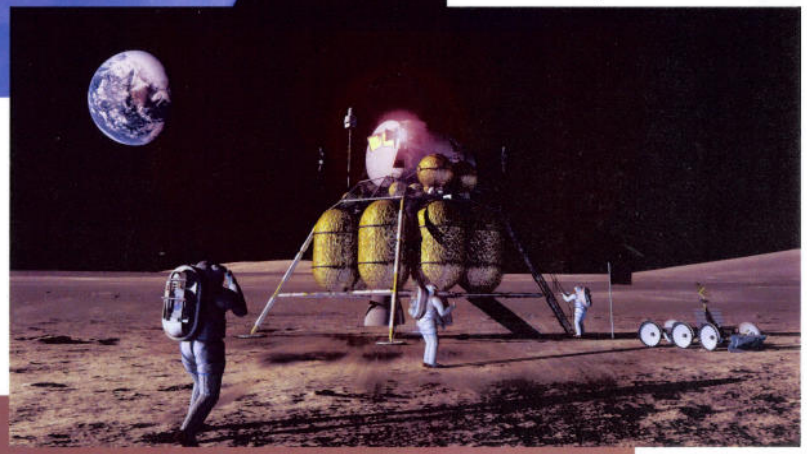


Exploration Architecture

Launch Vehicles

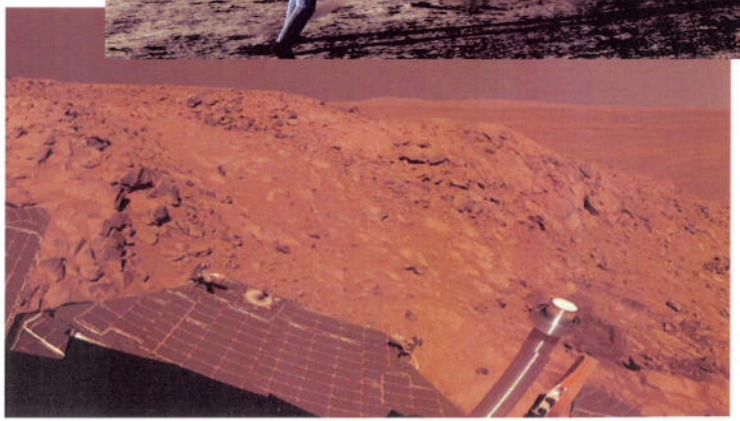
Lunar / Interplanetary Transfer

Lunar Surface Operations



Crew Exploration Vehicle (CEV)
ISS Operations

Planetary Operations
(Human/Robotic)



Future Exploration Mission Requirements Cannot Be Met with Conventional Materials

Vehicles and Habitats

- Reduced mass and volume
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multi-functionality
- Improved durability
- Environmental resistance (dust, atmosphere, radiation)

EVA Suits

- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance

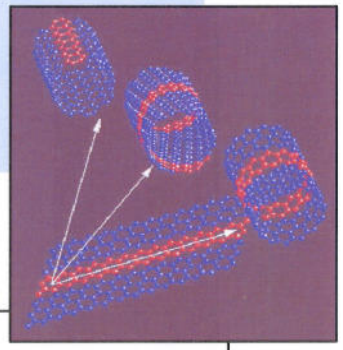
Satellites and Rovers

- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

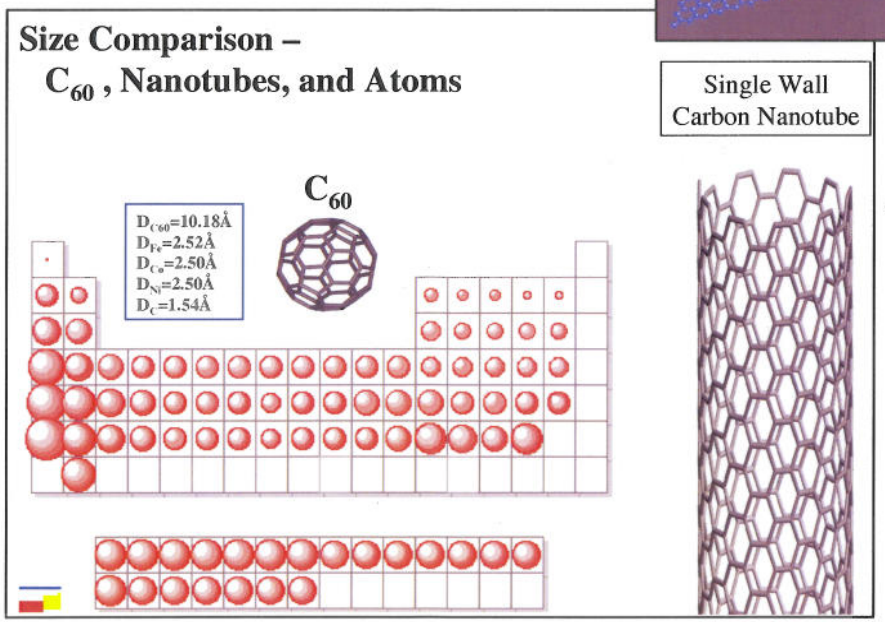
Nanomaterials: Single Wall Carbon Nanotubes

Unique Properties

- Exceptional strength
- Interesting electrical properties (metallic, semi-conducting, semi-metal)
- High thermal conductivity
- Large aspect ratios
- Large surface areas



Single Wall Carbon Nanotube



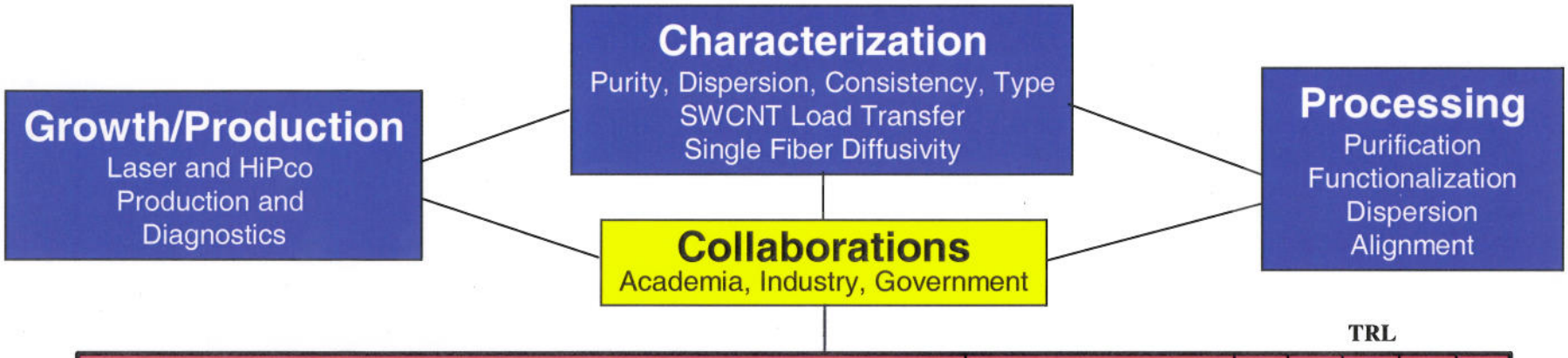
Possible Applications

- High-strength, light-weight fibers and composites
- Nano-electronics, sensors, and field emission displays
- Radiation shielding and monitoring
- Fuel cells, energy storage, capacitors
- Biotechnology
- Advanced life support materials
- Electromagnetic shielding and electrostatic discharge materials
- Multifunctional materials
- Thermal management materials

Current Limitations

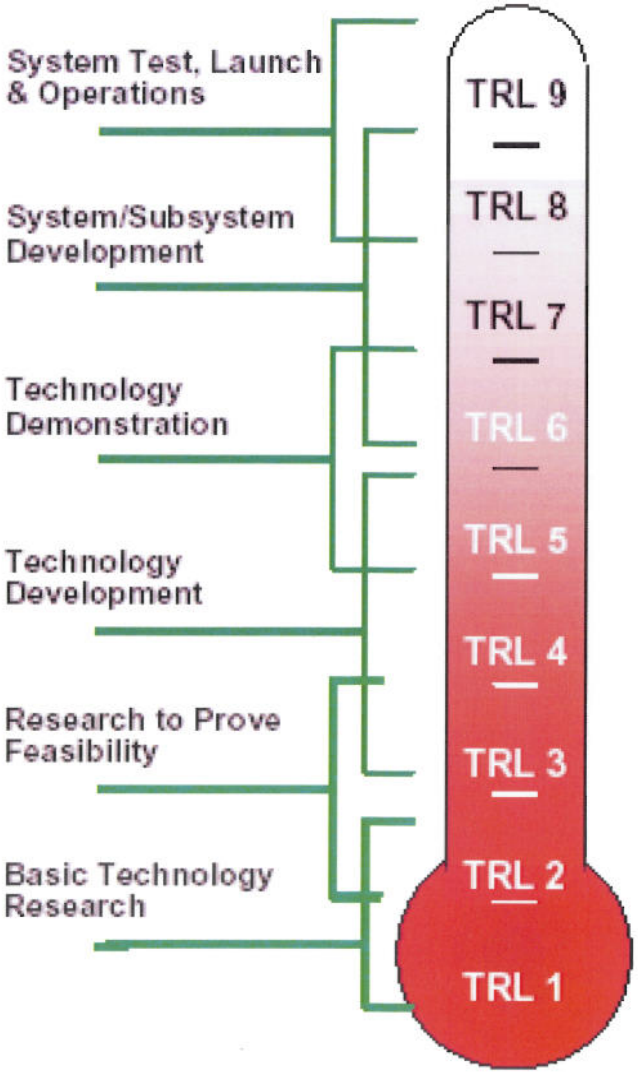
- High cost for bulk production
- Inability to produce high quality, pure, type specific SWCNTs
- Variations in material from batch to batch
- Growth mechanisms not thoroughly understood
- Characterization tools, techniques and protocols not well developed

Applied Nanotechnology at JSC: Fundamentals to Applications



APPLICATIONS	PARTNERS	TRL 1	2	3	4	5
Supercapacitors	EP, GRC, Industry	X	X	X	X	
ESD / EMI Shielding	EV, OA, Rice, UTPA, UTD, Industry	X	X	X		
Regenerable CO_2 Removal	EC, ARC, Rice, UTA Industry	X	X			
Proton Exchange Membrane – PEM - Fuel Cells	EP, GRC, Industry	X	X			
Water Disinfection & Recovery	EC, Industry	X	X			
Active / Passive Thermal Management Materials for Space	EC, Rice, Industry	X	X			
Multifunctional Materials: Thermal Radiation & Impact Protection (TRIPS)	ES3, ARC, Rice, Industry	X	X			
Nanotube-Based Structural Materials & Advanced Repair	EC, MA, ES3, Rice	X	X			
Radiation Dosimeter	NX, Rice, PV, Ames	X				

Technology Readiness Levels (TRL)



Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported

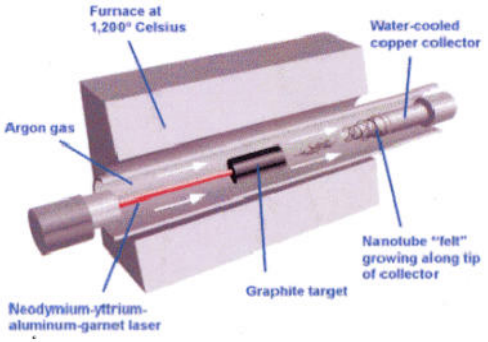
Growth, Modeling, Diagnostics and Production

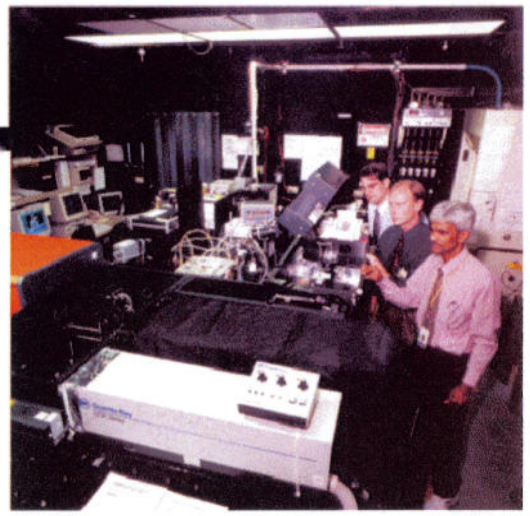
Objective: Ensure a reliable source of single wall carbon nanotubes with tailored properties (length, diameter, purity, chirality)

Laser Ablation

Graphite $\xrightarrow[\substack{4000\text{-}5000\ K\\ argon}]{Co,\ Ni\ Catalysts}$ fullerenes + SWCNT + impurities

- Batch process
- ~1g/day
- Large diameters (~1.4nm)





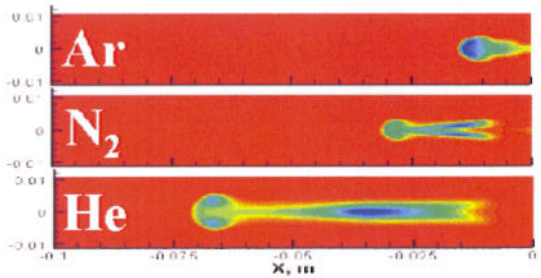
High Pressure CO (HiPco)

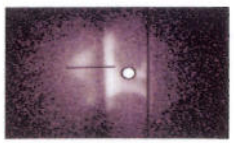
CO + CO $\xrightarrow[\substack{900\text{-}1200C\\ 10\text{-}40\ atm}]{Fe,\ Ni\ Catalysts}$ CO_2 + SWCNT + impurities

- Continuous process
- 10-100's g/day
- Small diameters (0.9nm)
- Company spin-off (CNI)

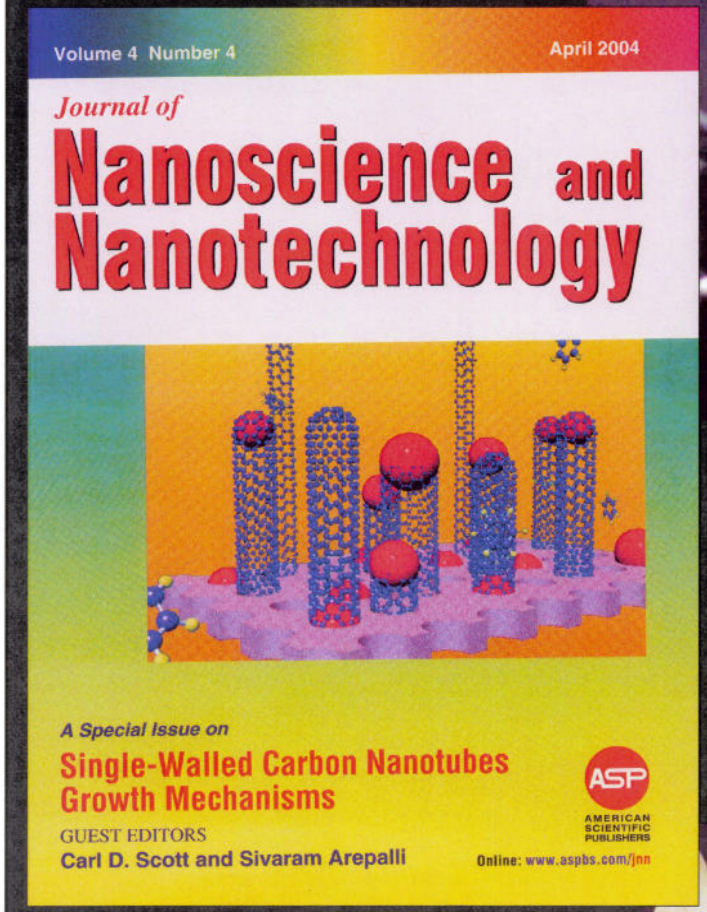
Rice Univ. & NASA → Carbon Nanotechnologies, Inc.

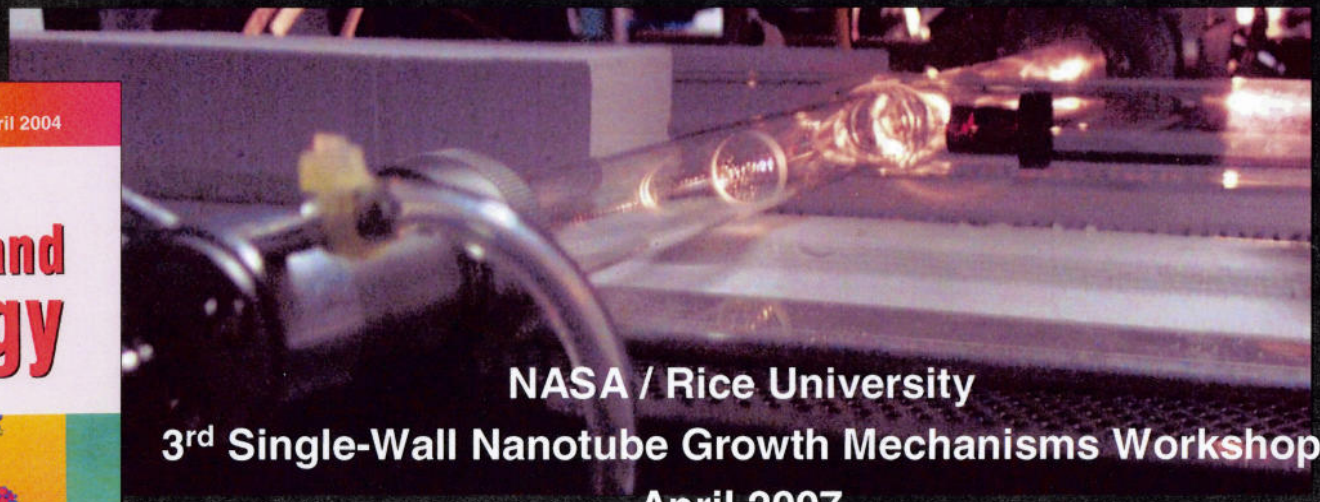
Modeling, Diagnostics, and Parametric Studies



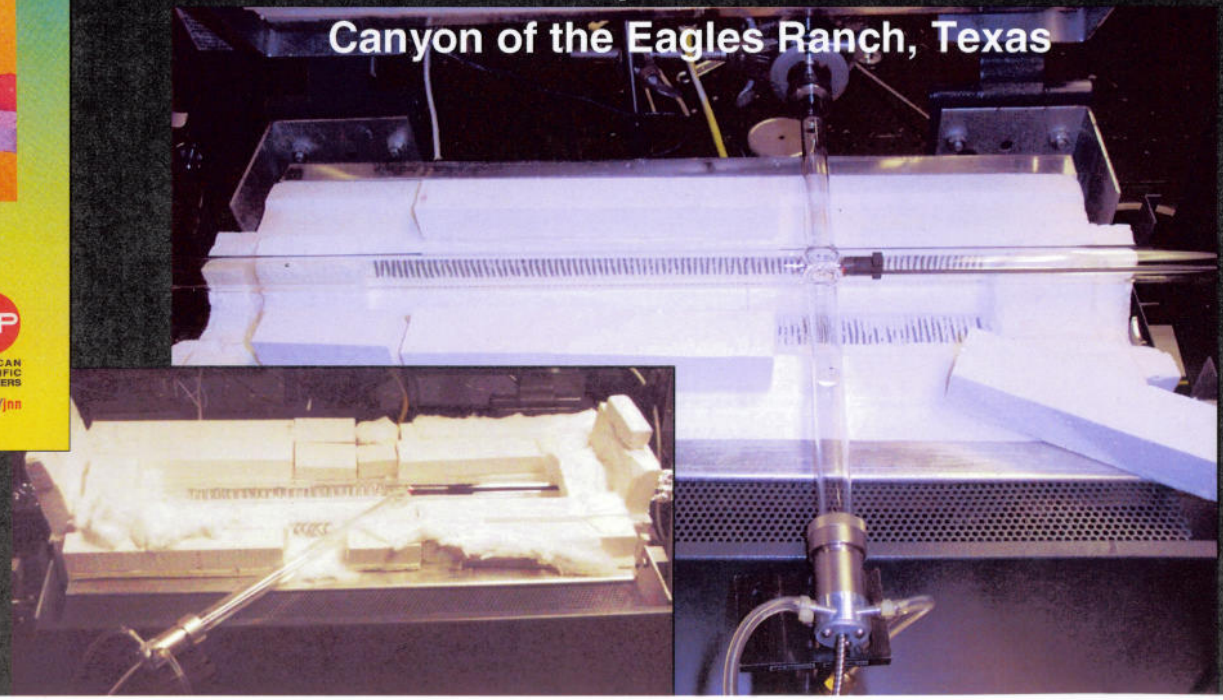


Growth, Modeling, Diagnostics and Production



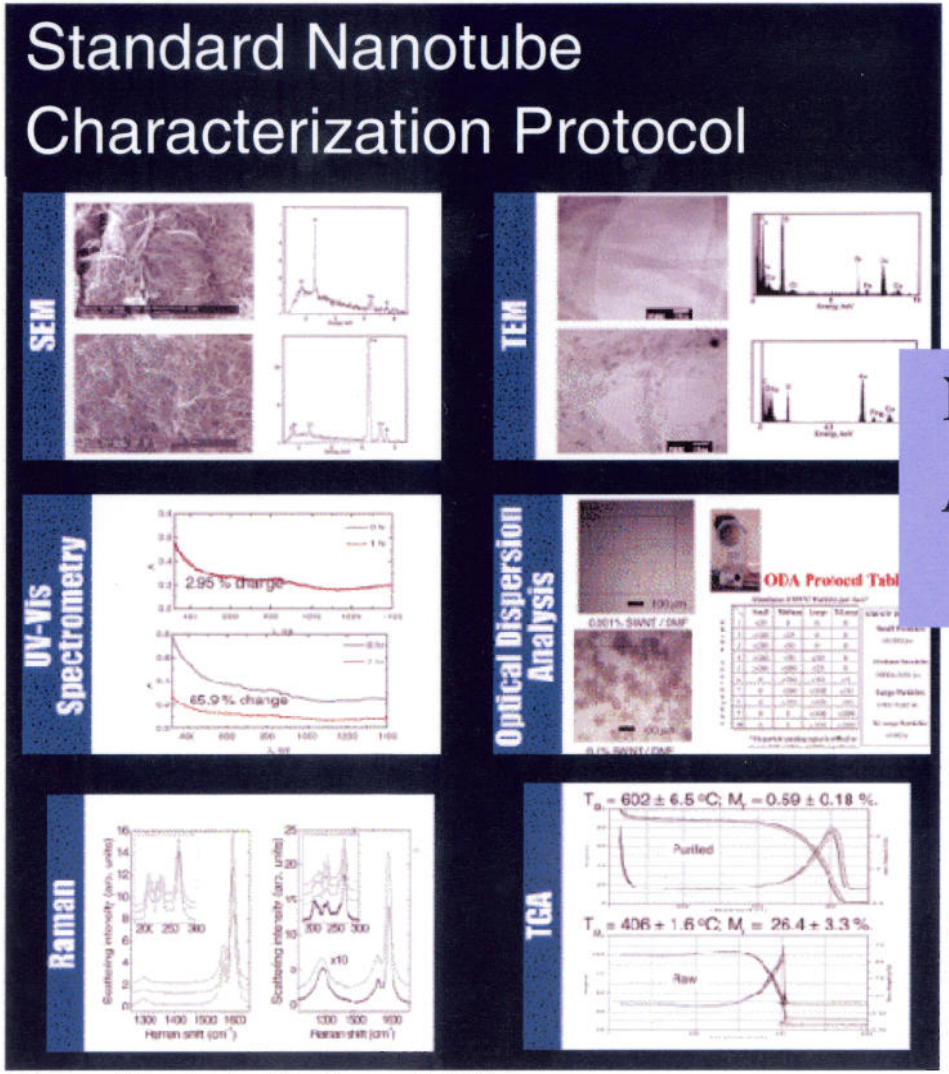


NASA / Rice University
3rd Single-Wall Nanotube Growth Mechanisms Workshop
April 2007
Canyon of the Eagles Ranch, Texas



Characterization: Purity, Dispersion & Consistency

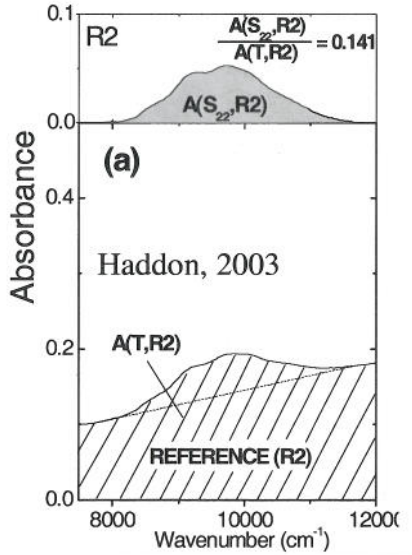
Standard Nanotube Characterization Protocol

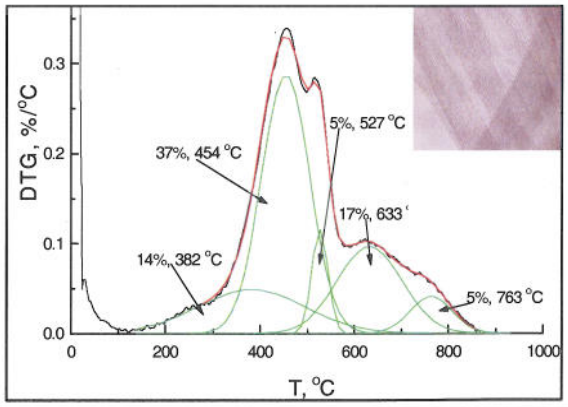


NIST
ANSI
ISO

Arepalli, et al., Carbon, 2004

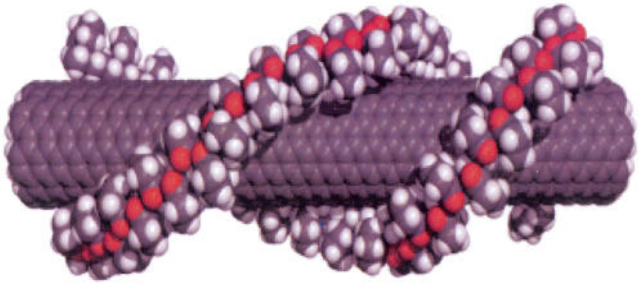
New Purity Reference Standard

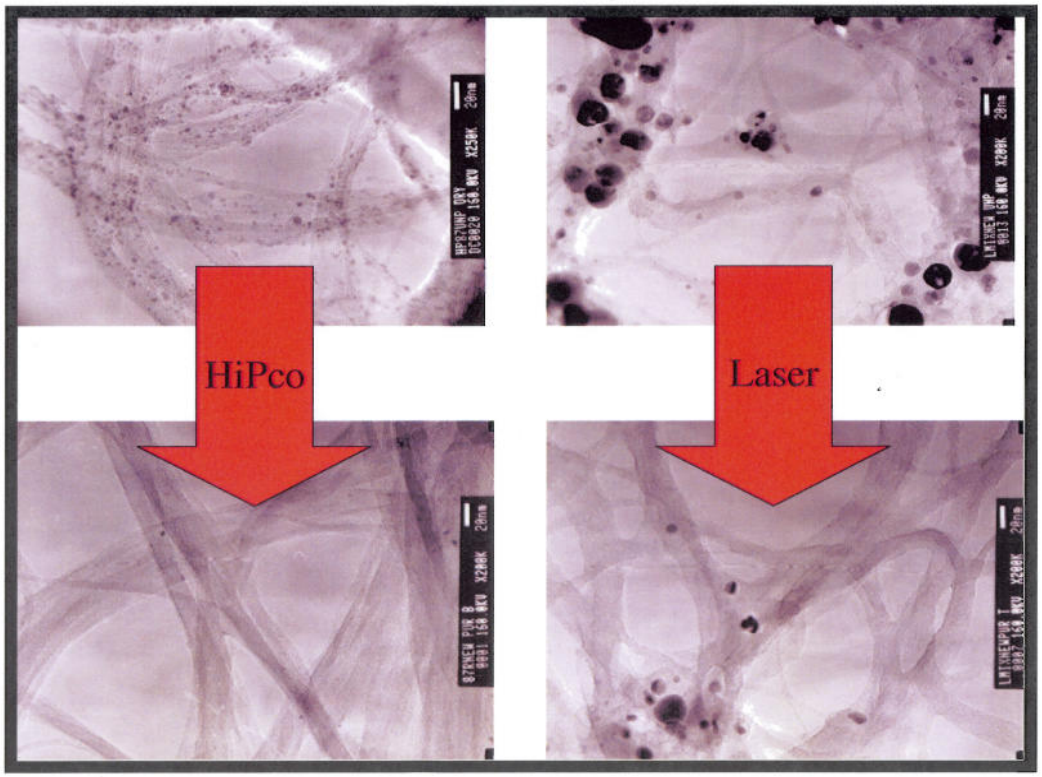


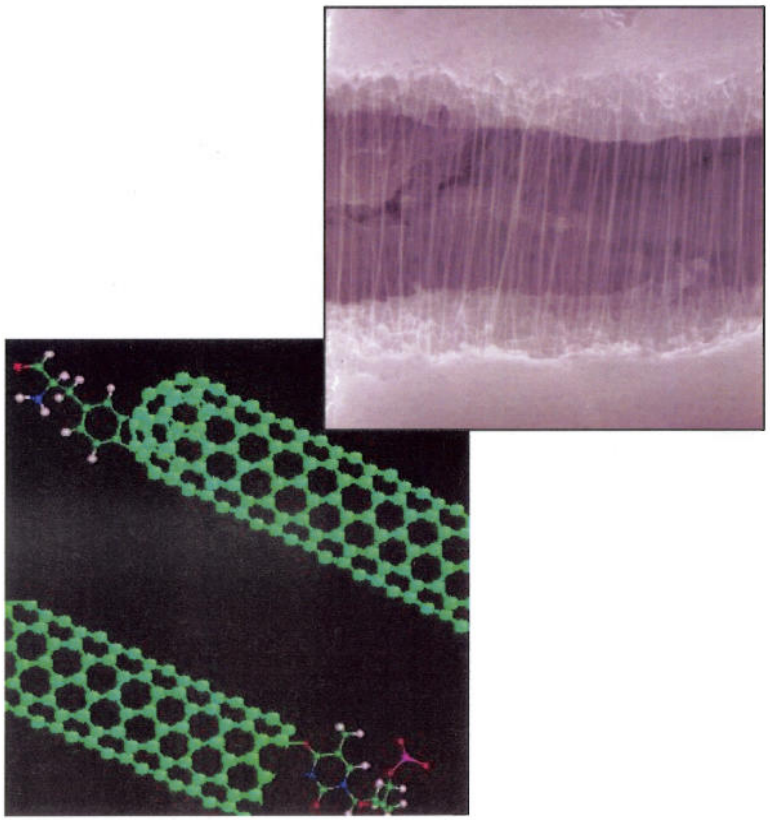


Processing

* Dispersion
* Purification
* Functionalization
* Alignment
* Surface Area







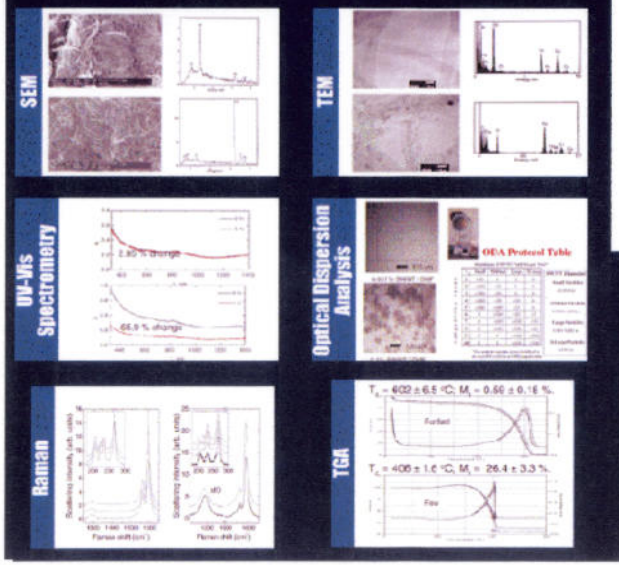
Nanoelectronics: Enabling Technologies

Nano-Fabrication

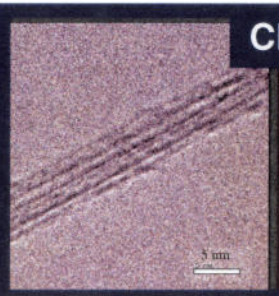
(10,10) Armchair Tube

Nano-Characterization

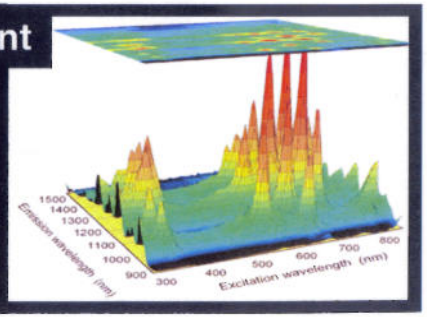
Standard Nanotube Characterization Protocol



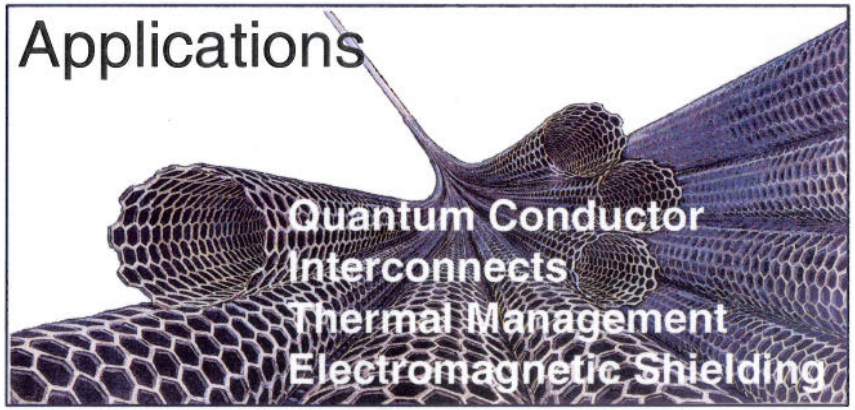
Type-Specific Nanotube Synthesis



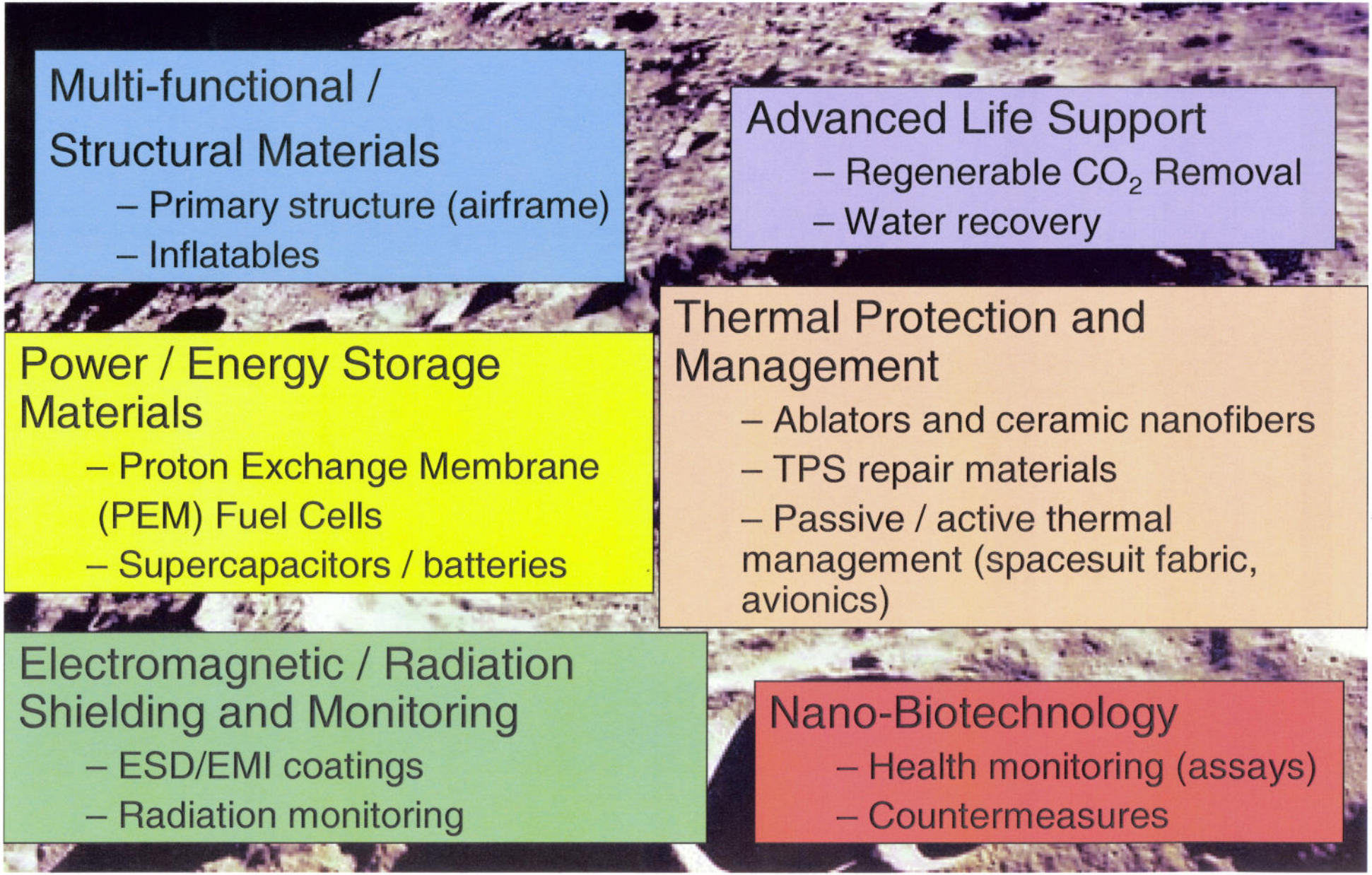
Chirality Assessment



Applications



Applications for Human Space Exploration



Multi-functional / Structural Materials

- Primary structure (airframe)
- Inflatables

Advanced Life Support

- Regenerable CO_2 Removal
- Water recovery

Power / Energy Storage Materials

- Proton Exchange Membrane (PEM) Fuel Cells
- Supercapacitors / batteries

Thermal Protection and Management

- Ablators and ceramic nanofibers
- TPS repair materials
- Passive / active thermal management (spacesuit fabric, avionics)

Electromagnetic / Radiation Shielding and Monitoring

- ESD/EMI coatings
- Radiation monitoring

Nano-Biotechnology

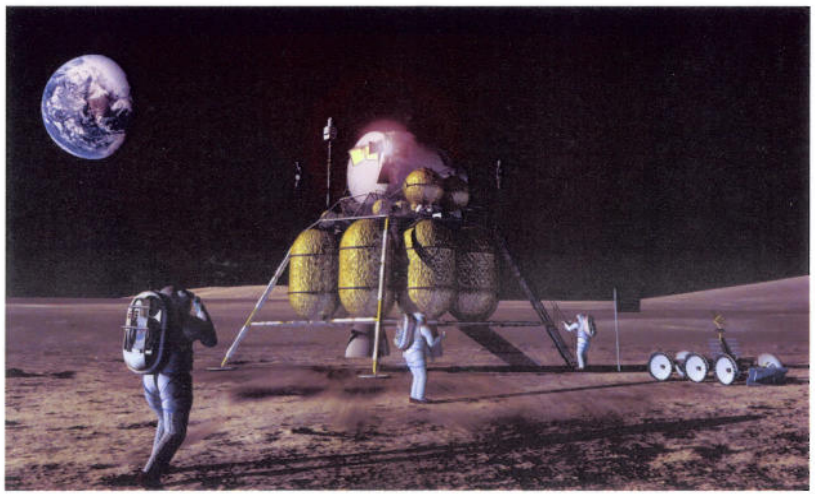
- Health monitoring (assays)
- Countermeasures

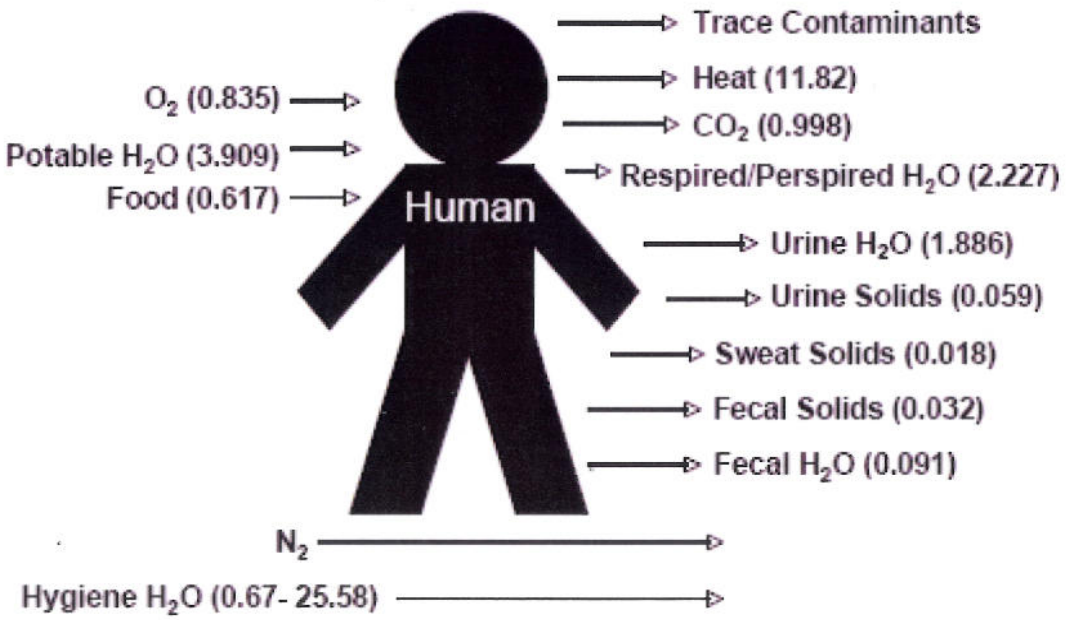
Exploration Life Support

CHALLENGE:

Supply the daily needs of humans for long duration missions

- Air Revitalization
- Food Management
- Solid Waste Management
- Thermal Control
- Water Reclamation





Human consumable and throughput values in kg/crewmember/day Klaus et al, 2005

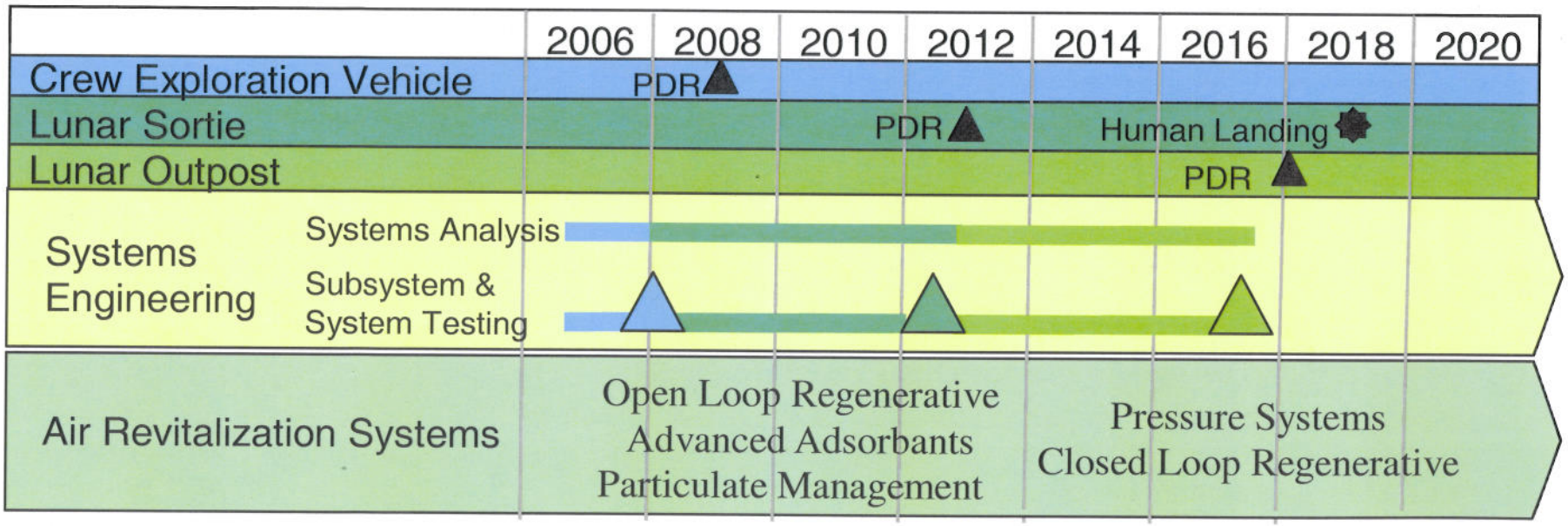
Exploration Life Support: Atmosphere Revitalization System

MISSION:

- Vehicle cabin atmospheric pressure & quality
- Atmospheric gas storage, supply and distribution
- Carbon dioxide partial pressure control
- Trace contaminant & particulate control
- Resource recovery, storage and distribution
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety

LiOH Canisters

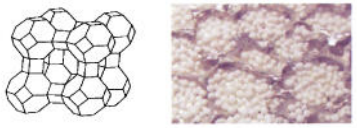
Experimental Regenerable System



Advanced Life Support: Regenerable CO_2 Removal

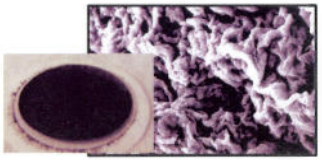
CHALLENGE:

- Long duration space flight requires a regenerable system for air revitalization
- NASA need: lower mass, higher performance, reduced volume



Current RCRS materials: Zeolites and amine-coated polymer beads.

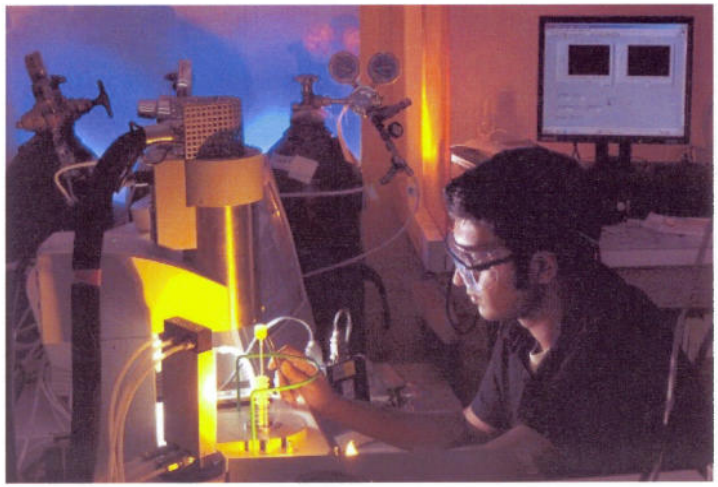
To be replaced by



Single Wall Carbon Nanotube (SWCNT) Structure

SOLUTION:

- Carbon Nanotubes: superior surface area & thermal conductivity
- Functionalized with CO_2 scrubbing chemistry – less volatile
- Suitable for both EVA and vehicle applications
- Applicability to smokestack applications on Earth



Micro-scale testing with thermo-gravimetric analysis

COLLABORATION:

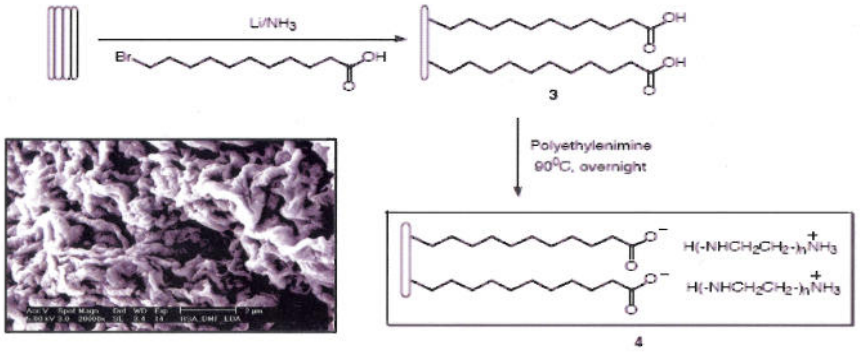
- Rice University: Nanotube functionalization
- UTA: Primary amine chemistry
- JSC (EC): Requirements for space systems
- NASA Ames: Nanomaterials for trace contaminant control system & CO_2 Sensors
- Energy industry participation interest

RICE UTA™ University of Hartford

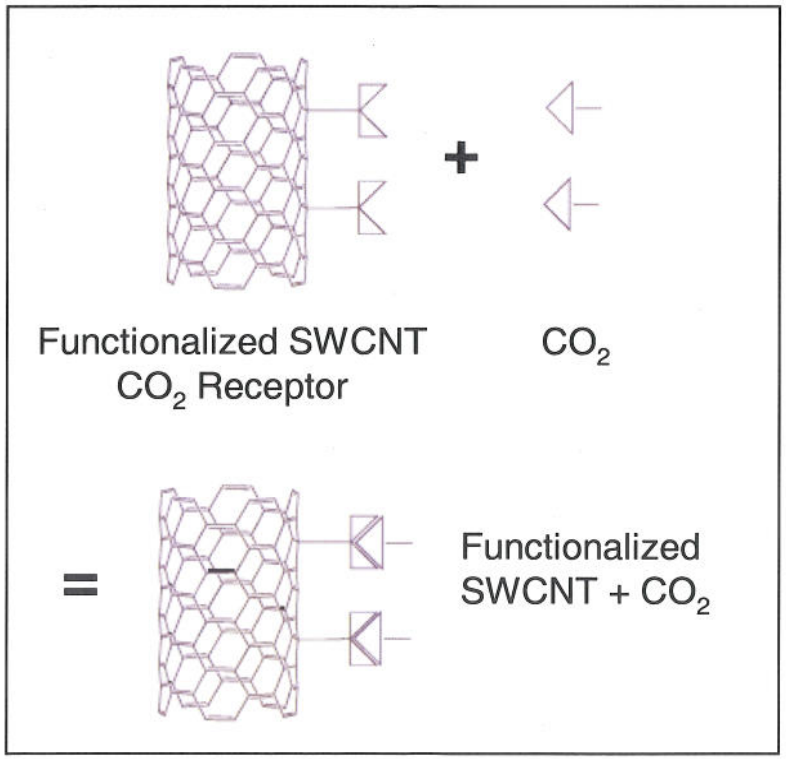
Exploration Life Support: Regenerable CO_2 Removal

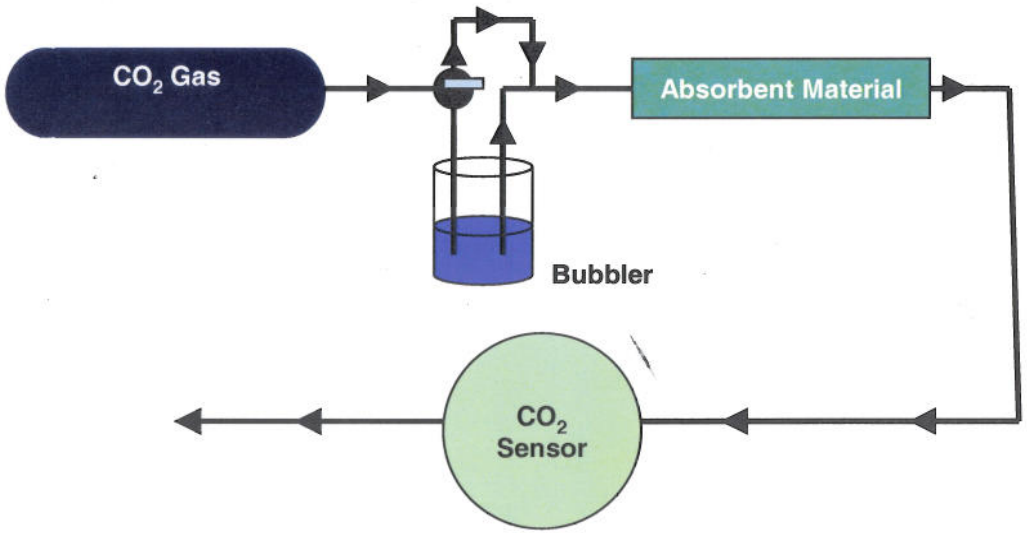
NanoMaterial Solution:

- Use SWCNT functionalized with CO_2/H_2O scavenging amines
- Amines require lower energy for regeneration than present molecular sieve
- Higher surface area reduces system size/ weight



Nanotube functionalization chemistry
(Chattopadhyay et al, 2005)

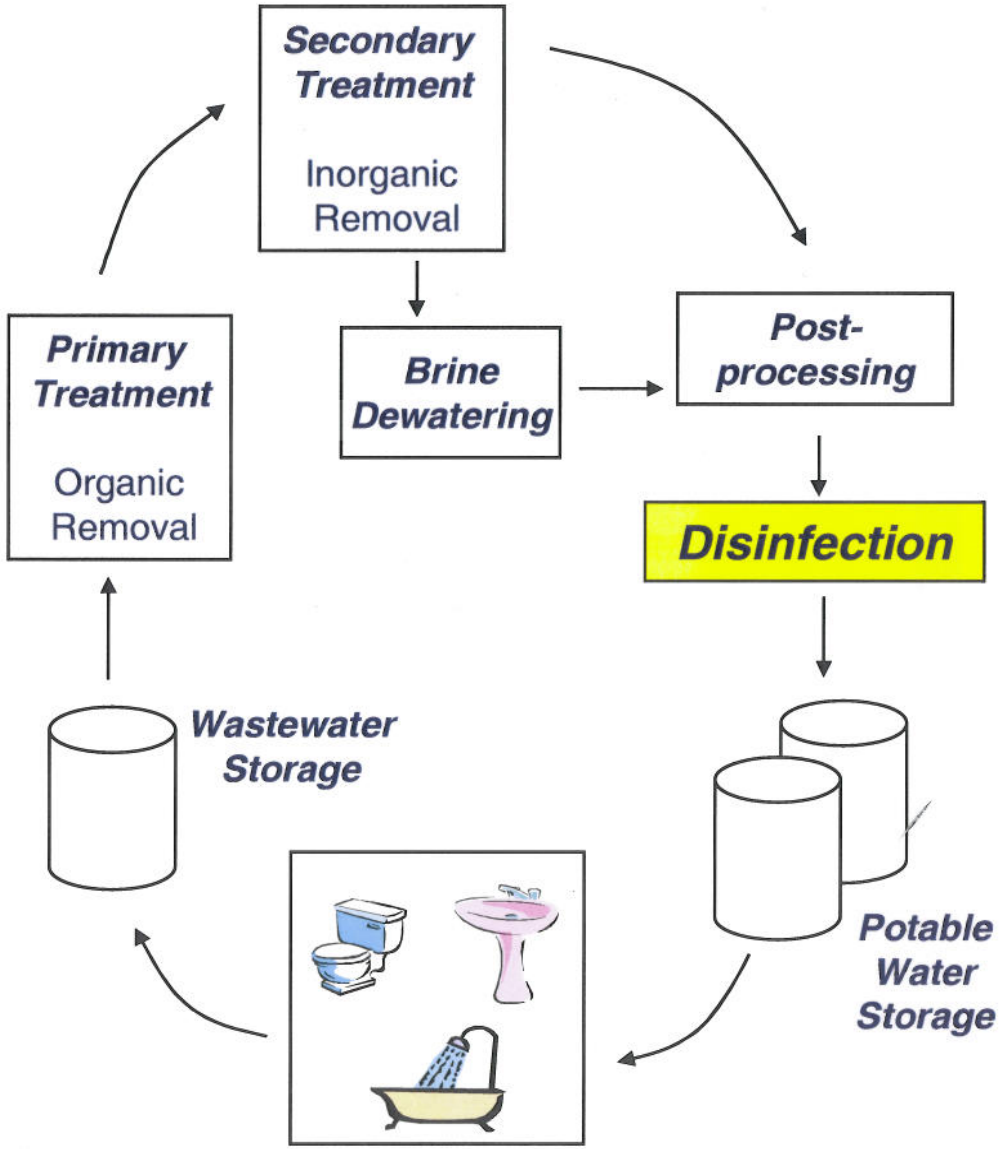




CO_2 capacity testing

Exploration Life Support: Water Recovery

- Transport and storage of wastewater from human interfaces
- Primary processing: organic and nitrogenous contaminant reduction
- Secondary processing: inorganic contaminant reduction
- Brine dewatering: water removal from highly concentrated brine
- Post-processing and disinfection: polishing to meet potability standards
- Storage and transport of potable water prior to consumption



Advanced Life Support: Water Disinfection / Recovery

CHALLENGE:

- NASA requires renewable chemical-free systems to purify water in space
- Current solution: Iodine – toxic to astronauts and non-regenerable

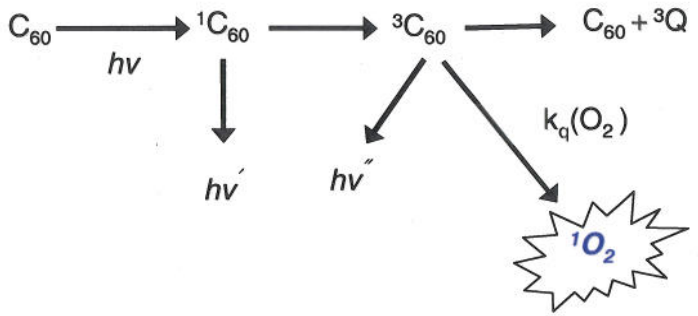
SOLUTION:

- C_{60} /fullerene enhances disinfection property of UV light
- Singlet oxygen production enhances the rate at which bacteria are killed
- Chemical-free system for closed loop water purification
- Commercial Potential - Portable water disinfection devices

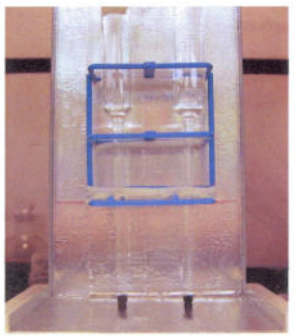
COLLABORATION:

- NASA JSC Advanced Life Support (EC)
- Rice University: C_{60} deposition

RICE



UV light energizes fullerenes. Upon relaxation, photons are emitted and the excited fullerenes interact with oxygen molecules in water to produce singlet oxygen.
Singlet oxygen kills bacteria.



Water purifier cell

UV Light source

Power & Energy: Supercapacitors

CHALLENGE:

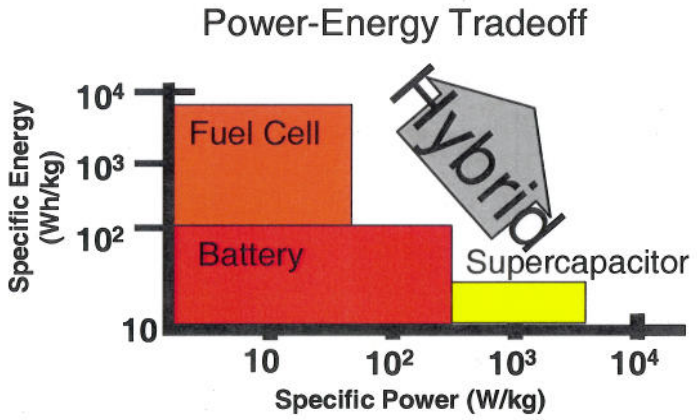
- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

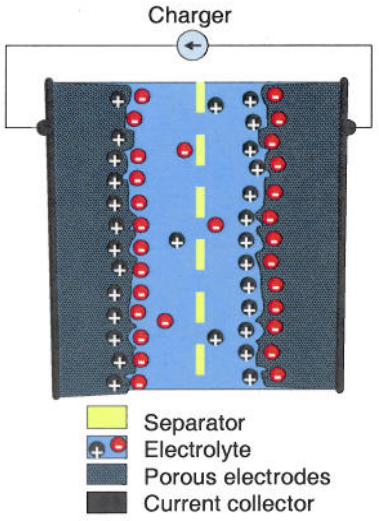
SOLUTION:

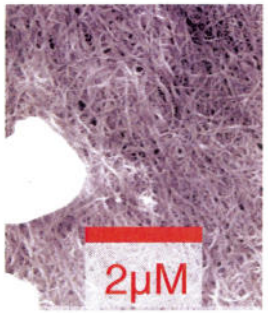
- Carbon nanotube surface area and nanoporosity superior to current materials for electrolyte ion support
- Carbon nanotube electrolyte supports: enhanced electrical and thermal conductivity
- Potential for enhanced performance and longer cycle life

COLLABORATION:

- NASA Glenn: Separator materials
- JSC (EP): Requirements
- Georgia Tech: Functionalized nanomaterials
- ReyTech Corp.: Improved fabrication & packaging







Nanotube electrolyte support

Supercapacitor test cell

Georgia Tech Research Institute

Power & Energy: Fuel Cells

CHALLENGE:

- NASA requires reliable, robust power sources suitable for both EVA and vehicle applications
- NASA requires increased power & energy densities, increased cycle life, reduced mass

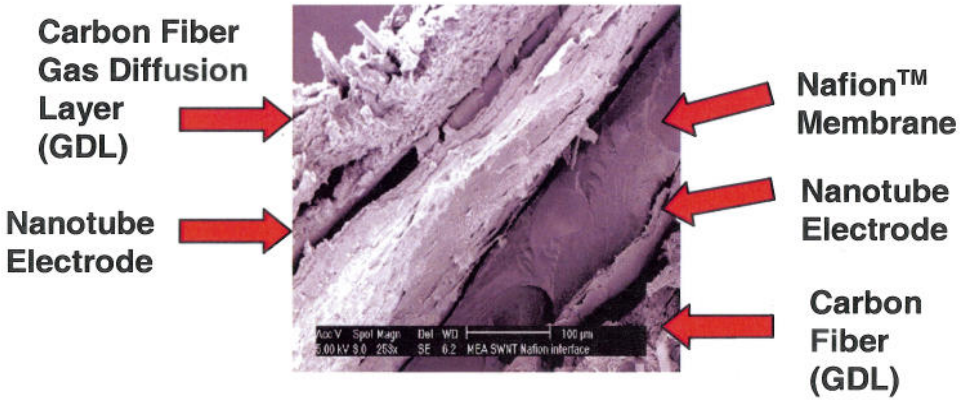
SOLUTION:

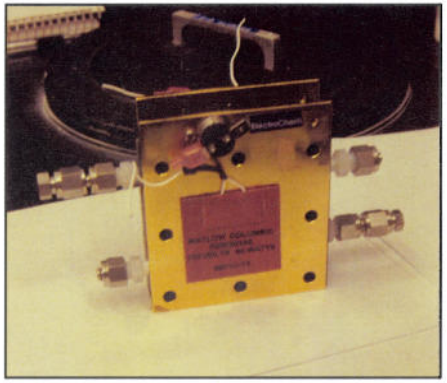
- Novel carbon nanotube high surface area, high thermal & high gas diffusivity catalyst support
- Reduced activation polarization – increased reliability
- Higher power density from more efficient utilization of platinum catalysts

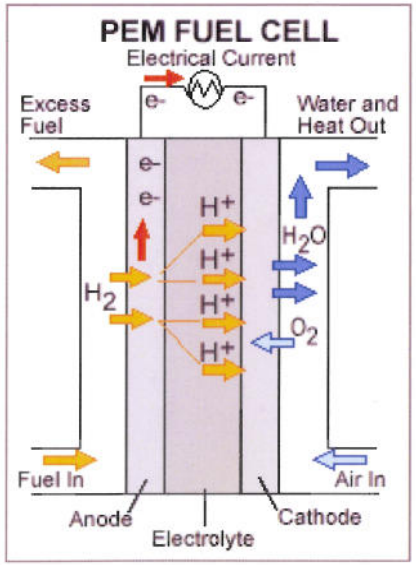
COLLABORATION:

- NASA Glenn: High temperature membranes
- JSC (EP): Testing, requirements

Prototype Membrane Electrode Assembly







PEM Fuel Cell Schematic
(Dept. of Energy)

NanoMaterials for EMI Shielding

CHALLENGE:

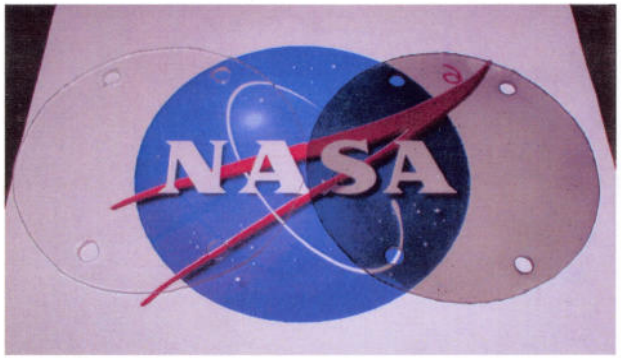
• Control of electromagnetic emission and susceptibility characteristics of electronic, electrical and electromechanical equipment and subsystems for space exploration

SOLUTION:

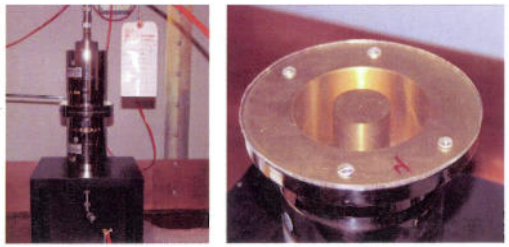
• Single-wall carbon nanotubes (SWCNT) offer low material density and high electrical conductivity
• Can be integrated into polymer matrices as well as applied onto surfaces as thin **transparent** coatings
• Cheap & ease of fabrication for application to off-the-shelf products: Laptops, PDAs etc.

COLLABORATION:

•UTD:	Nanotube materials
•UTPA:	EMI testing & test development
•U of Florida:	Nanomaterials functionalization
•Rice:	Nanomaterials functionalization
•JSC (EV):	Testing, requirements



Translucent Appliqués: Potential coatings for LCD screens



EMI testing in collaboration with UTPA

RICE

UTPA
The University of Texas-Pan American

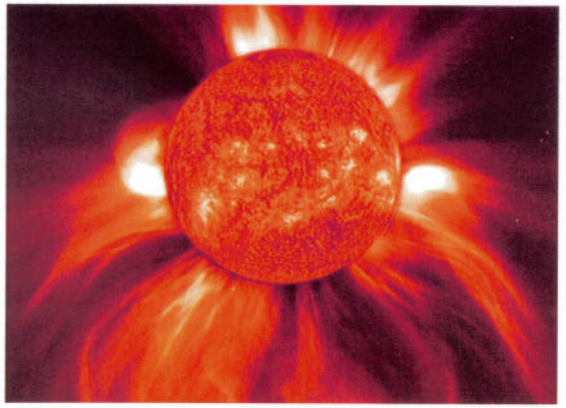
UTD

UNIVERSITY OF FLORIDA

Active Radiation Dosimeter

CHALLENGE:

- Acute radiation sickness poses a risk to astronaut health for interplanetary travel
- Currently no "real-time" personal radiation detecting sensor for extravehicular activity
- Current technologies lack desired sensitivity

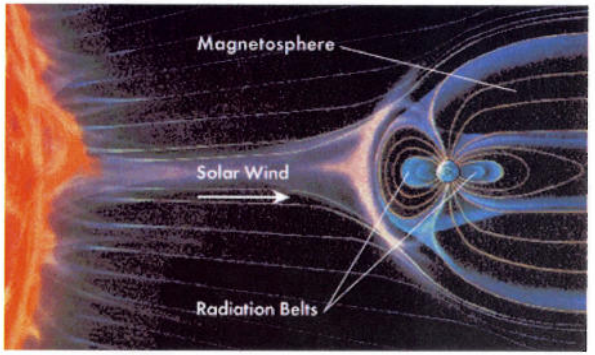


Solar Particle Event

SOLUTION:

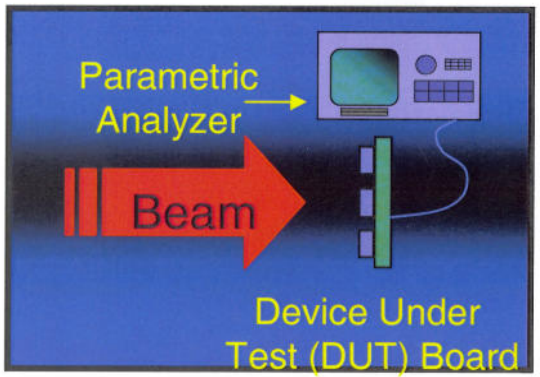
- Use radiation sensitive functionalized SWCNTs to measure radiation dose rates and total dose.
- High surface area nanomaterials can increase sensitivity

Earth's Protection



COLLABORATION:

• JSC (SF)	Dosimeter
• JSC (EB)	Sensors
• JSC (EC)	Advanced EVA
• NASA Ames	Gas sensors
• Rice Univ.	Nanotube functionalization
• PVAM	Radiation Testing



Radiation Testing

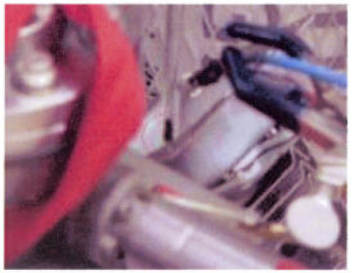
Advanced Thermal Protection System (TPS) Repair

CHALLENGE:

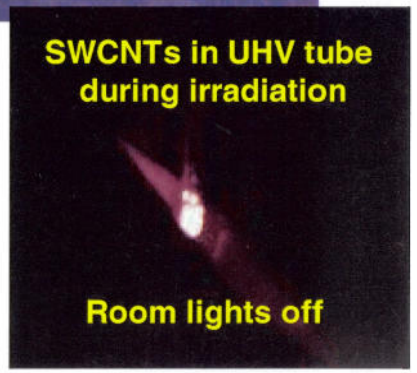
- Improve and expedite curing and repair processes for current missions
- Long duration missions need more effective repair processes: On Orbit/En Route/On the surface

SOLUTION:

- Use microwave energy to heat nanotubes in polymer and ceramic matrices for localized heating, curing & bonding
- Repair of RCC and tiles, CEV materials
- Potential commercial applications including composite curing



700 W
2.45 GHz



~ 1:1 Energy transfer in nanotubes

Microwaves:Heat

COLLABORATION:

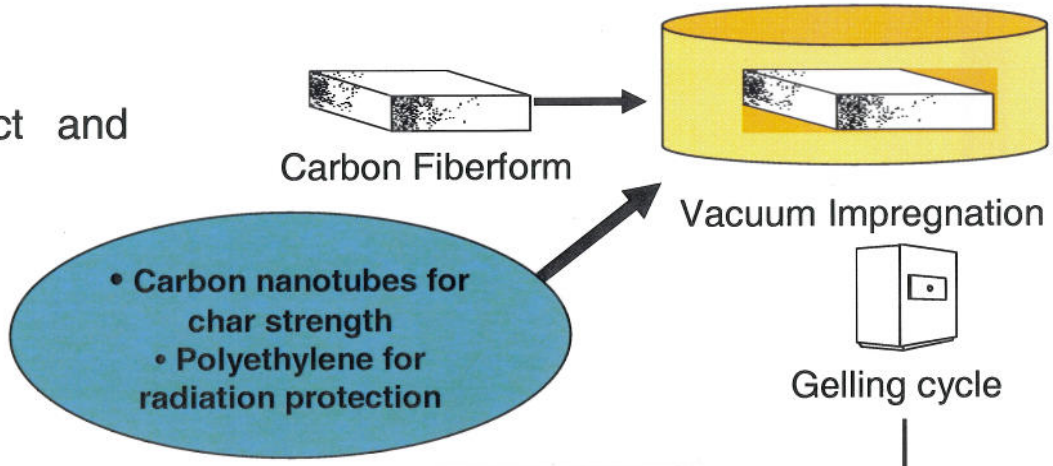
- Rice: Nanotube microwave research (Tour)
  Functionalized nanomaterials

RICE

Thermal Radiation & Impact Protection (TRIPS)

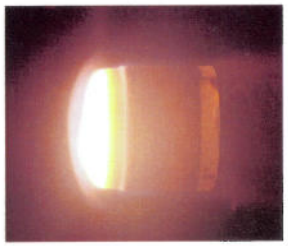
CHALLENGE:

- Thermal protection system with impact and radiation protection
- Lower weight = Greater performance
- Lower spacecraft complexity = Lower risk
- Lower risk = Greater safety



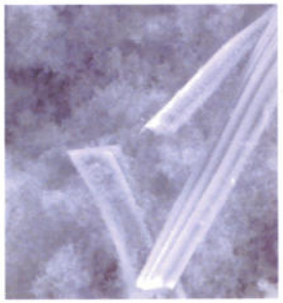
SOLUTION:

- Use SWCNT impregnated into Phenolic Impregnated Carbon Ablator (PICA) Thermal Protection System (TPS) – additional strength
- Enhanced radiation protection via integration of polyethylene
- Nextel and/or Kevlar fabric incorporated for impact protection



COLLABORATION:

- NASA Ames: TPS Lead
- JSC (ES3): Composites, Arc Jet Testing



PICA with phenolic resin impregnated

PICA - Fiberform before impregnation

Nanotechnology: Astronaut Health Management

Basic Biomedical Research

- The role that forces play on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

Personal Biomedical Monitoring

- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

Personal Countermeasures

- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

Major Medical Operations

- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

Life Support

- High surface area materials for CO_2 removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor/gases

Toxicology & Ethics

- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

Systems Integration

- Develop 'common toolkit' for bio-nano chemistry and assembly processes

JSC Nanomaterials Group Collaborations

Government

National Institute of Standards and Technology
- Development of nanoscale measurement standards (Frieman)

NASA Langley Research Center
- Production / purification (JSC) for use in SWNT composites (Siochi, Park, Smith)

Central Intelligence Agency
- Nanotube characterization (Carr)

Oak Ridge National Lab.
- CNT production, purification and characterization (Geohegan)
- Thermal characterization (Wang)

NASA Ames Research Center
- Nanotubes (JSC) for sensors / modeling of HiPco (Meyyappan, Srivastava)

National Renewable Energy Lab
- CNT Purification (Heben, Dillon)

NASA Glenn Research Center
- Functionalization, purification, high temp. mat'ls (Meador, Gray)

Air Force Research Lab.
- Composites, characterization, purification (Maruyama, Strong)

NASA Marshall Space Flight Center
- Nanotubes, MMCs (Gill, Hudson)

Naval Research Lab.
- Composites (Imam, Pehrsson)

Los Alamos National Lab
- Purification (O'Connell)

National Institute for Occupational Safety and Health
- Nanotube toxicology studies (Shvedova)

Academia

NASA-URETI: Texas A&M, Rice, UT Arlington, TSU, PrairieView A&M and UH
- Nanotube characterization
- Radiation protection
- Mechanics / composites

Rice University
- Advanced Nanotechnology Mat'ls and Applications (Smalley, Tour, Barrera)
- Computational Mat'ls Sci. (Yakobson)
- Nanoshells (Halas)

University of Houston
- GSRP, year 3 of 3 – Polymer chemistry, dispersion, composites (Mitchell, Krishnamoorti)

Michigan Tech
- Summer Faculty Fellow - Composites (Caneba)

UC Riverside
- Purification / characterization (Haddon)

Georgia Tech
- Nanotube composite films (Ready)

University of Paris 13
- Arc process (Farhat)

University of Pennsylvania
- CDDF - Thermal Mgmt. Mat'ls (Fischer)
- Composites (Luzzi, Winey)

University of Florida
- Isolated SWNTs (Rinzler)

University of Tennessee, Knoxville
- Nanoindentation (Penumadu)

Northwestern
- Nanomechanics (Ruoff)

University of Oklahoma
- Thermal stability of nanotubes (Resasco)

LeTourneau University
- Summer Faculty Fellow
  Nanotube growth process (DeBoer)

University of California - Davis
- Nanocrystalline Ceramics (Mukherjee)

Penn State
- Purification / characterization (Eklund)

University of Texas - Tyler
- Summer Faculty Fellow – CFD of Laser process (Greendyke)

Wake Forest
- Characterization of nanotubes (Carroll)

Industry

SouthWest NanoTechnologies, Inc.
- SBIR - Nanotube production (Resasco)

Carbon Nanotechnologies, Inc.
- Production, purification, applications (Smith)

Zyvex
- SBIR – Dispersion (Randall)

NanoTechnologies of Texas, Inc.
- SBIR – Conductive fabrics (Chibante)

Isotron
- EMI shielding

Hamilton-Sundstrand
- CO_2 Scrubber (Papale)

Resolution Performance Products
- Epoxy / nanotube composites (Stark)

Inorganic Specialists
- SBIR - Electrochemical capacitors (Firsich)

Nantero, Inc.
- NanoRAM development (Siegel)

ReyTech
- SBIR – Ultracapacitors (Reynolds)

Ionwerks
- Mass spectrometry (Schulz)

COI Ceramics
- RTF – Ceramic / nanotube composites (Riedell)

Nanospectra
- Thermal control coatings (Watkins)

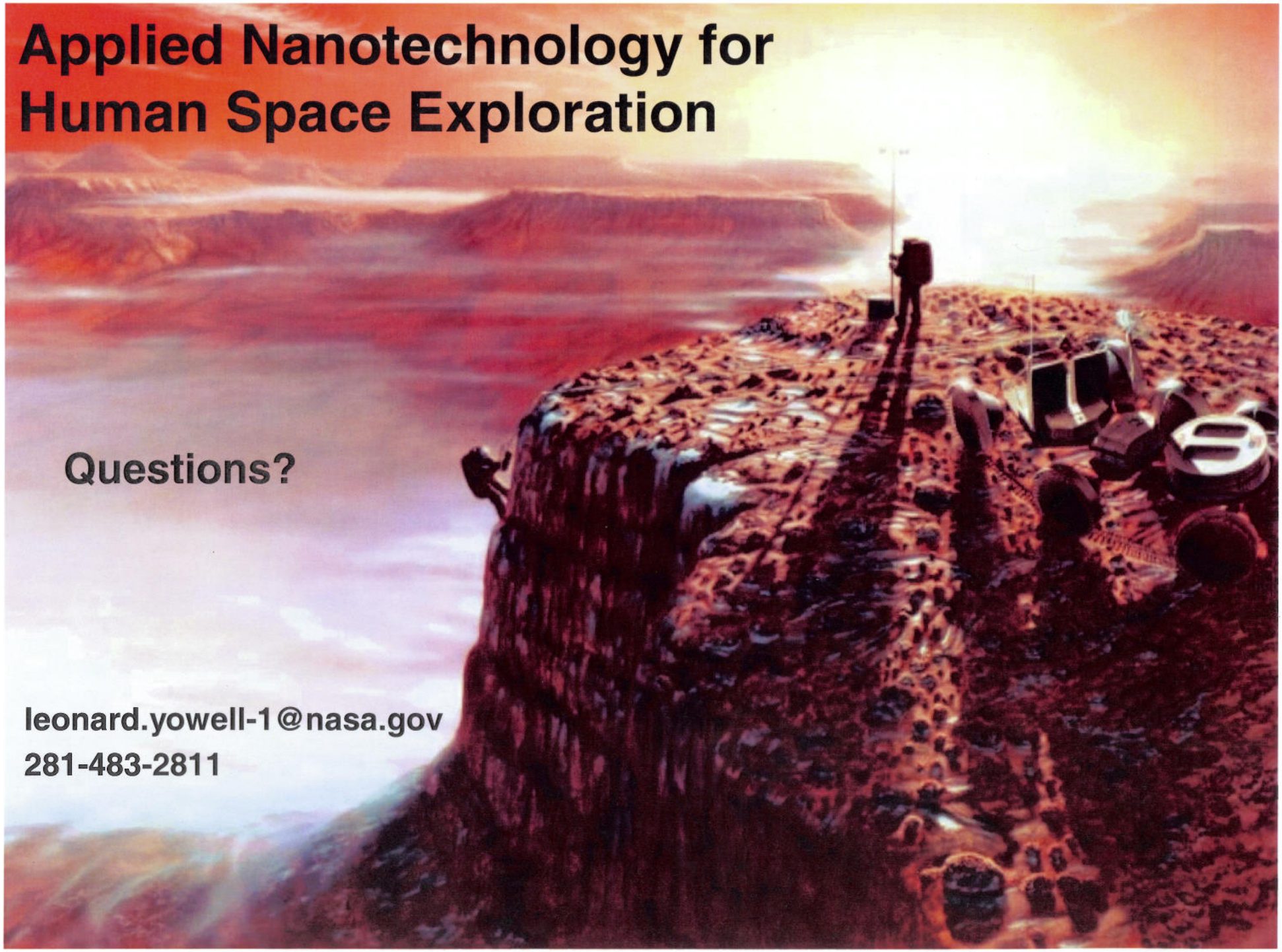
Eikos
- EMI Shielding (Glatkowski)

Honda
- Magnetic characterization (Harutyunyan)

GB Tech
- Fuel cells / CO_2 scrubber (Huffman)

Materials and Electrochemical Research
- SBIR - Nanotube production (Loutfy)

Applied Nanotechnology for Human Space Exploration



Questions?

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281-483-2811